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Published in:
IMAPS Nordic Annual Conference 2015 June 8-9, Helsingør

Publication date:
2015

Document Version
Peer reviewed version

Link to publication from Aalborg University

Citation for published version (APA):
Hygum, M. A., & Popok, V. (2015). Modeling of humidity-related reliability in enclosures with electronics. In J. Kutilainen (Ed.), IMAPS Nordic Annual Conference 2015 June 8-9, Helsingør (pp. 106-110). Red Hook: Curran Associates, Inc.

Modeling of humidity-related reliability in enclosures with electronics

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Abstract

Reliability of electronics that operate outdoor is strongly affected by environmental factors such as temperature and humidity. Fluctuations of these parameters can lead to water condensation inside enclosures. Therefore, modelling of humidity distribution in a container with air and freely exposed water is of importance for reliability engineering.

Reliability assessment of large complex systems is often done by dividing the complex into decoupled subsystems. The reliability of such system is then obtained by combining the reliability of each subsystem. In this paper we set up a framework to predict humidity-related reliability of a printed circuit board (PCB) located in a cabinet by combining structural reliability methods and non-linear diffusion models. This framework can, thus, be used for reliability prediction from a climatic point-of-view. The proposed numerical approach is then tested to estimate the reliability of a case example with liquid water at the bottom of a cabinet and PCB positioned on one of the walls. The water vapor profile inside the enclosure is calculated using a diffusion equation whereas the release of vapor from the water surface is modeled using statistical rate theory. The novelty in this work lies within the reliability prediction based on physical modeling of the climate in the system of interest.

Key words: Modeling of humidity distribution, Statistical rate theory, Humidity-related reliability, Enclosures with electronics.

1 Introduction

A significant issue in reliability engineering is the problem of climatic simulations which includes the aspect of relative humidity of air. Some electronics operate outdoor and are, thus, exposed to daily alterations of temperature and humidity. It is a well-known fact that a humid climate greatly affects the reliability of electronics. Catastrophic failure can occur if water condenses on a PCB short-circuiting the electronic devices. Corrosion is, likewise, one more well-known failure mechanism. If the circuit board is exposed to a high relative humidity (RH) moisture can diffuse through the encapsulation and oxidize the wiring. See for example [1] for various reliability models for PCB with RH as the stressing factor. Since completely hermetic boxes or cabinets are quite expensive, accurate reliability models based on the physical climatic models of such systems are of importance.

Much attention has been paid to predict the moisture absorption by the electronic packaging, the moisture distribution inside the encapsulating material and circuit boards, see e.g. [2-6]. However, approaches to predict the reliability using climatic simulation for enclosures have not been intensively studied. This type of simulations should include appropriate physics-based model for the humidity distribution and evolution as a first step. Descriptions of humidity distribution affected by freely exposed water surfaces require accurate models for the vapor flux at the water-interfaces. For this framework the statistical rate theory (SRT) approach for the interface flux can be used [7–9]. It is experimentally verified and it offers climatic modeling of enclosures without any fitting parameters, making it to be a general-purpose method applicable for reliability prediction and as a design tool.

Following the philosophy suggested in [10] proper design for reliability should originate from physical understanding of the system. Therefore, the model presented in this paper is SRT-based approach for the simulation of the humidity profile in a container of given geometry with a condensed water and the simulated humidity distribution can be applied for the prediction of failure of electronics. Thus, the tool provides opportunities for intelligent packaging design and/or reliability assessment.

In this paper the case example is restricted to an enclosure with no temperature gradients at steady state and diffusion is considered as the main contributor to the transport of water vapor in air. Thus, it mimics an outdoor cabinet at night with no operating electronics. However, the proposed framework is not restricted to such relatively simple cases and it can be extended to more complex situations, which e.g. include convection [11].

It is worth mentioning that the novelty of this work lies within the combination of humidity modeling and reliability prediction. This enables reliability assessment with humidity as the stressing factor strictly based on physical models for humidity migration.

2 Theory

The humidity distribution in the system of interest was modeled using a diffusion equation with a source term, representing the vapor flux at the water interface. A sketch of the system is shown in figure 1. It represents a rectangular box with water condensed at the bottom, an opening (hole) in one of the walls and a circuit board located on the other wall. This section presents some key equations important for understanding the developed model.

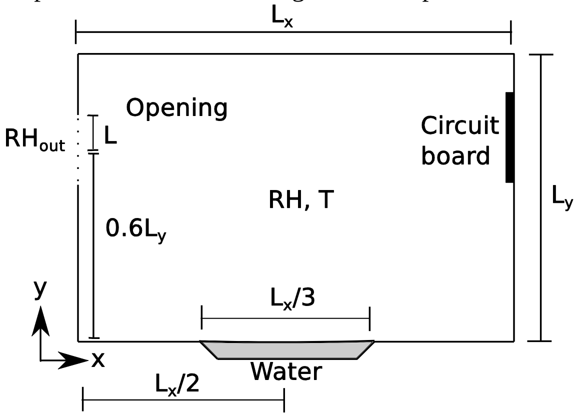

Figure 1: Schematic of the enclosure. See the text in Section 3 for the description of notations.

2.1 Diffusion theory

The transport of water vapor can be modeled as movement of a diluted species in air. This is governed by the continuity equation [12]:

$$\frac{\partial c(\vec{r},t)}{\partial t} + \vec{\nabla} \cdot \vec{J}(\vec{r},t) = Z(\vec{r},t), \qquad (1)$$

where c is the concentration of water vapor, $\vec{r}$ is the position and t is the time. $\vec{J}$ is the vapor flux and Z is the source term which represents the water surface. The flux is due to sheer diffusion:

$$\vec{J}(\vec{r},t) = -D_C \vec{\nabla} c(\vec{r},t), \qquad (2)$$

with D_C to be the diffusion coefficient. Z in equation (1) is based on the expression provided in [9]. The following expression for the magnitude of molecular flux orthogonal to the water surface is used [9]:

$$J_{SRT} = K_e \left(exp\left(\frac{\Delta S}{k_B}\right) - exp\left(-\frac{\Delta S}{k_B}\right)\right), \qquad (3)$$

ΔS is the interfacial entropy change, k_B is Boltzmann's constant. The first term in equation (3) is responsible for the evaporation and the second one for the condensation at the interface. K_e describes the rate to which molecules interact with the water-air interface and it is given by

$$K_e = \frac{p_{v,e}}{\sqrt{2\pi m k_B T_l}}, \qquad (4)$$

where m is the molecular mass, T_l is the temperature of the liquid and $p_{v,e}$ is the vapor pressure at equilibrium [9]. For a constant temperature, it can be shown that ΔS reduces to

$$\frac{\Delta S}{k_B} = \ln\left(\frac{p_{sat}(T_l)}{p_v}\right) + \frac{V_l}{k_B T_l}(p_l - p_{sat}(T_l)), \qquad (5)$$

with p_{sat} to be the saturated vapor pressure, p_v to be the vapor pressure and V_l to be the molar specific volume of water [11].

In order to know RH at the circuit board location it is necessary to know the RH distribution in the entire enclosure. Simultaneously solving equations (1) - (5) allows to predict the water vapor concentration, and thereby the RH spatial profile.

2.2 Reliability theory

Reliability prediction must allow for stochastic uncertainties. The reason for uncertain inputs could be due to variation in production parameters but also uncertainties regarding the usage of the system. Furthermore, for reliability modeling, a failure model is described by the limit-state equation $g(X) = 0$, with X as a realization vector of random variables [13]. The limit-state function can be defined as

$$g(X) = R(X) - L(X), \qquad (6)$$

with $R(X)$ to be the resistance and $L(X)$ to be the loading of the system [13]. The probability of failure is, thus, given by

$$P_f = P(g(x) \leq 0)$$
$$= \int \dots \int f_X(x_1, .., x_N)\, dx_1, .., dx_N, \qquad (7)$$

with $f(x_1, \dots, x_N)$ to be the joint probability density function of the random variables [13].

The probability of failure can be well-approximated by sampling of R and L. With N trials conducted, the probability of failure is approximately given by

$$P_f = \frac{N_f}{N}, \qquad (8)$$

where N_f is the number of trials for which $g(X) \leq 0$ out of the N trials. The sampling procedure is thus continued until the wanted accuracy of P_f is obtained [13]. The probability of failure is thereby determined using a physical model for the system with stochastic inputs.

This approach is quite general but here we limit the reliability issue to the humidity inside enclosures. The presence of the water can be thought of as a loading of the system, increasing the RH inside the enclosure, whereas the opening can be seen as resistance of the system, lowering the RH inside the enclosure. Thus, we consider a given value of RH to be the failing criterion. In other words, as soon as RH reaches this value at the location of a circuit board it should fail. RH is simulated using the approach briefly described in section 2.1.

3 Modeling

In moisture-related reliability, the RH is of interest. It is given by

$$RH = \frac{p_v}{p_{sat}}, \quad (9)$$

with the saturated vapor pressure for water vapor given as [14]

$$p_{sat}(T) = 2.53 \cdot 10^{11} e^{-\frac{2.501 \cdot \frac{10^6}{461.5}}{T}} [Pa], \quad (10)$$

The vapor pressure p_v follows the ideal gas equation:

$$p_v = cRT, \quad (11)$$

where R, here, is the gas constant. To predict the humidity distribution, the diffusion constant of water vapor in air is needed. At atmospheric pressure, it has been experimentally determined to be

$$D_{H_2O,air} = 1.87 \cdot 10^{-6} \cdot T^{2.072} \left[\frac{m^2}{s}\right], \quad (12)$$

which holds in the temperature range 282-450K [15].

The steady-state water vapor distribution was obtained using the finite volume method. The iteration approach was an over relaxed Gauss-Seidel scheme with a relaxation factor of $\omega = 1.9$. The water vapor flux at the water-air interface was calculated using the Newton-Raphson method. For more details on the iteration scheme, see e.g. [16] or [17]. Furthermore, for computational reasons the model is kept two dimensional.

In the model three stochastic variables were considered. The half-width length, $\boldsymbol{L}$, of the opening in the enclosure, the temperature T and RH outside, RH_{out}. In table 1 the simulation parameters for the stochastic variables are given.

Table 1. Simulation parameters for stochastic variables.

VARIABLE	DISTRIBUTION	MEAN	STD. DEV.
$\boldsymbol{L[L_x]}$	Log Normal	0.0135	$1.35 \cdot 10^{-6}$
$\boldsymbol{T[K]}$	Normal	303	10
$\boldsymbol{RH_{out}}$	Normal	0.6	0.02

At the walls of the enclosure no-flux boundary conditions were applied. For the opening the following concentration boundary condition was used:

$$c_0 = RH_{out} \frac{p_{sat}}{RT}. \quad (13)$$

Finally, a failing criterion must be defined. Here, we put the criterion to be a maximum value of relative humidity RH_f at the bottom of the circuit board, located $L_y/3$ below the top wall of the enclosure. Estimation of RH_f is beyond the tasks of the current paper. Some examples will be discussed in the next section.

A flowchart of the solving procedure is shown in figure 2.

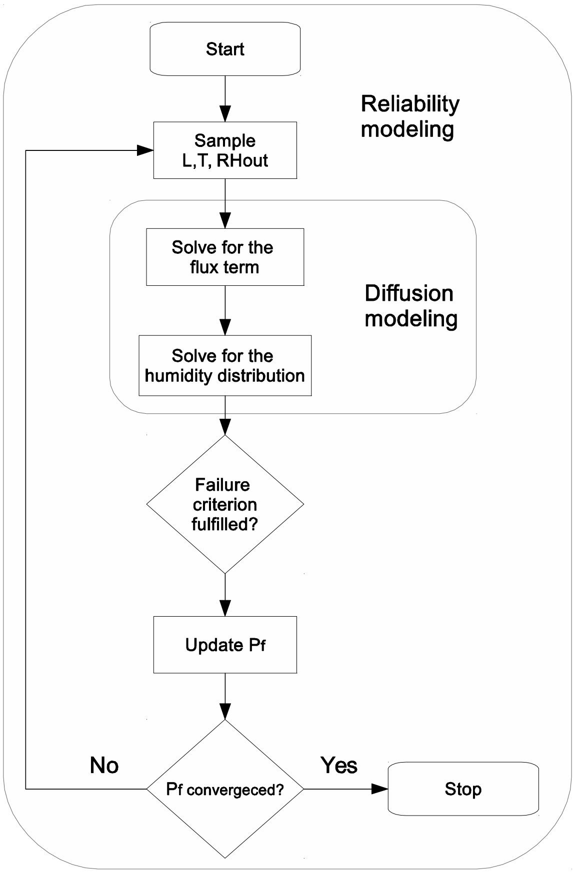

Figure 2: Illustration of the solving procedure.

4 Results

The diffusion problem was solved using 100 control volumes of equal size in each direction. Every length in the x-direction is normalized to L_x and likewise for the y-direction. Finally, the convergence criterion for the diffusion problem was set so that on average the change in the water vapor concentration at the control volumes was $\Delta c < 10^{-4} mol \cdot m^{-3}$.

A RH profile, generated by the sampling procedure, for a case with the stochastic inputs sampled to be $T = 300K$, $RH_{out} = 0.62$ and $L = 0.0133 L_x$ is shown in figure 3. One can see that the RH is highest just above the water surface and lowest at the opening, as expected.

Histograms of all the sampled values of T, RH_{out} and $\boldsymbol{L}$ for the simulation with $RH_f = 0.9$ are presented in figures 4, 5 and 6, respectively. The histograms are shown with a rescaled frequency in order to compare with the associated probability density functions (PDF) for the stochastic inputs. The rescaling is done so that the total area of the bins is equal to unity. From figures 4-6 it is clear that the sampling procedure has generated enough data for the histograms to recover the associated PDFs.

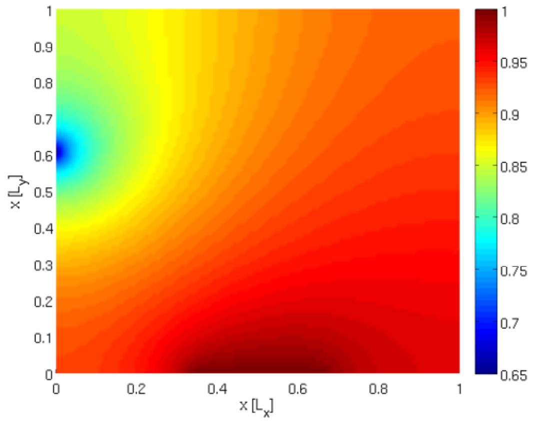

Figure 3: Simulated RH profile in the enclosure with be $T = 300K$, $RH_{out} = 0.62$ and $L = 0.0133L_x$.

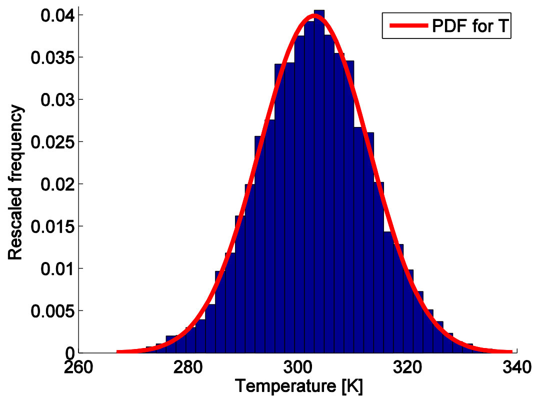

Figure 4: Histogram of the sampled T.

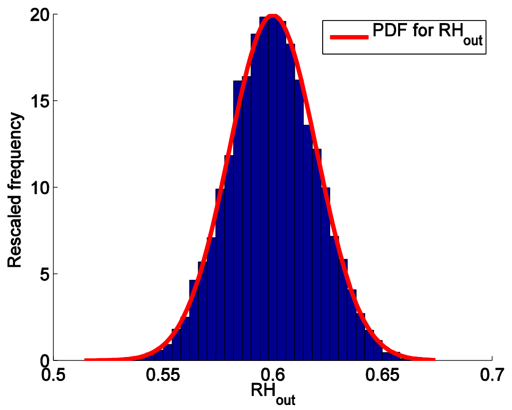

Figure 5: Histogram of the sampled RH_{out}.

The probability of failure for three different failing criteria was modeled with a convergence match of 10^{-5}. The obtained P_f corresponding to different RH_f are given in table 2. The table shows how the choice of the failing criterion directly affects P_f. It is found that small increase of RH from 0.90 to 0.95 as a failing criterion significantly decreases the probability of failure. Further increase of RH_f leads to a significantly smaller failure probability of 0.044.

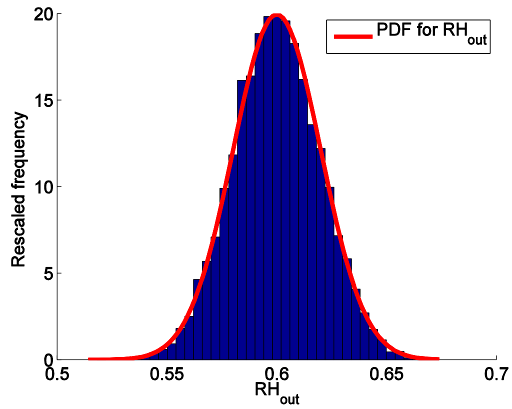

Figure 6: Histogram of the sampled L.

Table 2. Simulated failure probabilities

FAILING CRITERION	P_f
$RH_f = 0.9$	1.000
$RH_f = 0.95$	0.320
$RH_f = 0.98$	0.044

Humidity-related failing criterion can be found experimentally for a particular type of PCB and operational conditions. One can see some examples in [18] where the RH issue was combined with presence of chemicals (residuals of organic acids after soldering). Overcoming of RH_f does typically not lead to immediate catastrophic failure. However, leakage currents are significantly and stepwise increased promoting electrochemical migration and accelerated corrosion which finally causes the failure.

5 Conclusion

Reliability prediction model based on climatic simulations in enclosures is described. The climatic simulation predicts humidity distribution in a box of given configuration. Diffusion is considered to be the predominant transport mechanism of water vapor in the enclosure with the water vapor flux at the water-air interface described according to SRT. Thus, this part of the model is based on the appropriate description of physical phenomena in the framework of fluid dynamics. The failure probability is calculated by a Monte Carlo method, thus, linking the calculated RH at the given location with the humidity-related failing criterion for the electronic circuit. Hence, the humidity-related reliability of the device inside an enclosure can be estimated. The developed framework for the reliability prediction is not limited to only humidity. Any other failure criteria can be used in the similar way. The predictions can be also developed for more complex geometries of enclosures.

Further improvements of the framework can be done by including thermal gradients and convection of the air inside the enclosure. The probability of failure, predicted by our Monte Carlo approach, can also be compared to other reliability prediction methods, for example, the first- or second order reliability method known from structural reliability [13].

Acknowledgements

This work is a part of research activities within the Center of Reliable Power Electronics (CORPE) funded by the Danish Strategic Research Council.

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